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NASA TT F-11, 631

Translation of "Inzhektsiya v Zamknutuyu Magnitnuyu Lovushku s Dvukhzakhodnym Vintovym Polem"
In: Fizika Plazmy (Plasma Physics),
"Nauka" Press, Moscow, 1966, pp. 7-19

GPO PRICE $ _____

CFSTI PRICE(S) $ _____

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

FACILITY FORM 602

N68-22330 (ACCESSION NUMBER) (THRU)

19 (PAGES) 1 (CODE)

✓ (NASA CR OR TMX OR AD NUMBER) 25 (CATEGORY)

MAY 1968

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 APRIL 1968

INJECTION OF A PLASMA INTO A CLOSED MAGNETIC TRAP WITH A DOUBLE-HELIX FIELD

by G. M. Batanov, S. Ye. Grebenshchikov, M. A. Ivanovskiy, I. S. Sbitnikova, G. I. Fedyanin and I. S. Shpigel'.

ABSTRACT. Experimental study of various plasma-injection approaches applied in closed magnetic traps with a double-helix field. The methods discussed include (1) injection into a programmed magnetic field, (2) injection along a cluster of magnetic-field lines of force expanded outside the magnetic-field perimeter, and (3) injection by colliding plasma fluxes in the transverse magnetic field of a toroidal trap. Strong effects of a helical external magnetic field on the plasma containment time, density, and distribution over the trap cross section are established. It is believed that effective plasma injection into closed magnetic systems can be achieved when these methods are developed further.

INTRODUCTION

The problem of generating energy by means of a fusion reaction /7* has been attracting the attention of physicists of many countries during the past decade. Though basically simple, the concept of a thermonuclear reactor has encountered enormous obstacles so far, largely because of the difficulty in creating a "working body". The production of pure plasma, thermal insulation, heating, the study of the nature of the instabilities of plasma configurations, and the methods for eliminating these instabilities--such are the principal problems currently facing plasma physics. The solution of the problem of thermal insulation is apparently related to a correct choice of magnetic trap. One of the possible systems which would provide for adequate confinement of plasma is a toroidal trap with helical magnetic fields (stellarator). So far, research on the behavior of plasma under such circumstances has been conducted at Princeton University (U.S.A.), where it was shown (see, e.g., [1]), that plasma created by ohmic current flowing in a gas is very short-lived and that there is absent also the effect of rotary transformation upon elimination of the toroidal drift (the effect of the stellarator field). The life-span of the plasma, in the opinion of the authors of [2], is determined by the Bohm formula. The mechanism of the origin of anomalous diffusion is so far not understood. However, there exists a number of hypotheses. For one thing, it is possible that anomalous diffusion is due to the oscillation of the ionosonic waves. A supposition was also suggested dealing with the incitation of plasma oscillations by escaping electrons generated during the passage of the ohmic current through the plasma [3].

* Numbers in the margin indicate pagination in the foreign text.

Some of the hypotheses explaining the short life-span of the plasma assume that the presence of instabilities resulting in abnormal losses is related to the method of producing the plasma within the trap itself--specifically, to the ohmic heating current and the presence of a lateral electric field. In this connection it can be assumed that generating the plasma within the confines of the magnetic trap by some other means would make it possible to avoid setting up instabilities and would thus permit a study of the properties of a helical magnetic field in a closed magnetic trap.

Apparently, plasma injection can be one of such methods. At the present time there exists a number of methods for filling a magnetic trap with hot plasma. Actually, the problem of injection is the result of the following physical considerations. The movement of a charged particle in a quasi-constant and quasi-homogenous magnetic field is adiabatic ($\mu = W_\perp / H = \text{const.}$, where μ is the magnetic moment constituting the adiabatic constant). According to the Lieuville theory, a particle proceeding on an adiabatic course, must--once it has covered a closed trajectory--return to its point of origin (the injector). Therefore, to trap such a particle requires the action of some kind of irreversible mechanism which would alter the field or the state of the particle. Such a mechanism could be constituted by a break in the adiabacity of the magnetic moment (alteration in transversal energy or in the magnetic field, provided that

$$\left(\frac{\partial W_\perp}{\partial t} > \omega_H W_\perp, \quad \frac{\partial H}{\partial t} > \omega_H H\right) \qquad /8$$

and, secondly, a change in the state of charge of the plasma particle e/m. Moreover, in considering the injection of plasma (as distinct from the injection of individual particles), it is indispensable to take into account quantitative factors which significantly alter the conditions for containing the plasma.

The great existing variety of injection methods can, in our opinion, be separated into two principal trends: a) generation of low-density plasma within the trap; and b) injection of dense plasma from the outside.

The following methods are among those of the first category:

1) Dissociation of fast atoms or molecules in the residual gas or in the gas-discharging arc. [4] and [5];

2) Ionization of atoms in a high state of incitation (principal quantum number $n \simeq 9 \div 11$). [6];

3) Ion magnetron. [7].

The second trend in injection methods is only just beginning to take form. It includes such methods as:

1) Injection of plasma from a titanium source into a system of the "plug-o-tron" and "anti-plug-o-tron" type. [8].

2) Collision of plasma streams in a transversal magnetic field [9] and [10].

3) Injection of plasma by means of a curvilinear magnetic conductor [11] and [12].

Also being studied at the present time are collisions of clots of plasma and the interaction of plasma streams in magnetic fields of different configurations.

Plasma being injected into a closed magnetic trap must possess the following properties:

1) It must be sufficiently homogenous in its content (hydrogen or deuterium)and must contain a minimal amount of impurities. The percentage of ionization must be close to 100;

2)Its temperature must be sufficiently high so as to eliminate losses due to normal diffusion in a magnetic field;

3)The plasma must possess a high degree of conductivity (and hence have a high value of T_e) in order to make sure that the polarization due to the toroidal effect is eliminated.

4) Once a plasma has filled a toroidal trap, there should be no signs in it of any noticeable lateral electric fields ($e\varphi \ll kT$).

If all of the above requirements could be met, it would be possible to conduct fairly accurate research into the behavior of plasma contained in a closed magnetic trap. However, at the present time, it is practically impossible to fulfill all of these conditions. For this reason the problem of injection is studied in separate parts, each seeking to clarify a different phase of the phenomenon. In studying the principle of the possibility of plasma injection, one is also forced to compromise somewhat with the conditions listed above.

The selection of the injection method depends upon the characteristics of the trap which it is planned to use in the experiment: the size and duration of the magnetic field, its configuration, and the geometric and structural parameters of the installation.

The present paper discusses the results of investigations using several different methods of plasma injection in a toroidal device with a double-helix magnetic field [13]:

plasma injection into a programmed magnetic field; /9

plasma injection along a tube of the lines of force of a magnetic field expanded beyond the trap;

collision of plasma streams in a transversal magnetic field of the trap.

EXPERIMENTAL RESULTS

1. Injection of plasma into a programmed magnetic field.

This method of injection is based upon an irreversible change in the configuration of the magnetic field in a certain area of a closed stellarator field during the injection.

Experiments to investigate the behavior of plasma during its rapid compression by an external azimuthal magnetic field (θ-pinches, installations of the "Scilla" type), have shown that, at the instant of maximum field, the compressed plasma takes the form of a thin string concentrated along the axis of the system. Experiments with rapid compression were conducted in large magnetic fields (tens of kilo-oersteds), in a low vacuum (10^{-1} to 10^{-2} mm. of hg.) No experimental data is available as to non-electrode discharge of plasma previously injected into a vacuum with a relatively low magnetic field (in the kilo-oersted range). For this reason it appeared of interest to conduct an investigation dealing with plasma confinement precisely under these conditions.

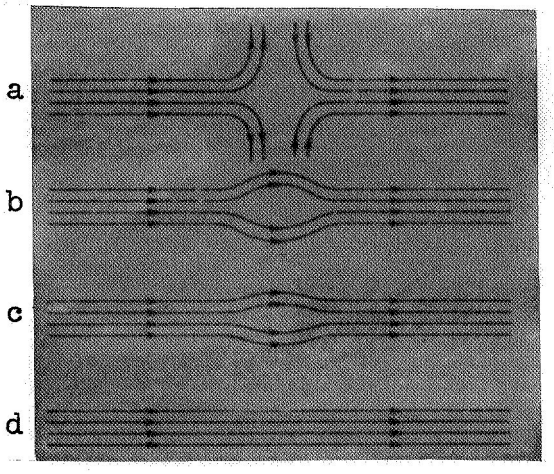


Fig. 1. Magnetic field topography in an installation with a programmed magnetic field.

Experiments with injection were carried out in a model installation [14]. Fig. 1 shows the topography of the magnetic field at different points in time. The magnetic field is homogenous, quasi-constant in time, and has "wells" in terms of both time and space. The injection of plasma occurs at the instant when, along the axis, the field equals zero (Fig. 1, a). There follows a rapid increase in the magnetic field, leading to a straightening of the density of the lines of force and the resulting compression of the plasma.

(Fig. 1, b - d). The magnetic system of the experimental installation consists of two parts: a solenoid, creating a quasi-constant magnetic field, and two compensating loops, which provide time and space modulation of the field in the area of the injection. Fig. 2 gives the graphs showing the changes in time in the magnetic field in the central area of the system, with plasma injection occurring at instant t^*. The vacuum chamber placed in the solenoid consists of /10
a glass tube having a diameter of 120 mm. and a length of 2200 mm. The injection is made from two diametrically arranged spark sources of the plasma. The basic measurements were conducted with the aid of a luminescent probe [15] or large, locally screened, annular laminated probes. These measurements have shown that in selecting a certain rate of injection, an effective confinement of plasma occurs, and a cylindrical stream is formed spreading along the lines of force of the magnetic field. Fig. 3 shows an instantaneous electronic image of the plasma stream at a distance of 60 cm. from the plane of the injection, 6 and 30 μ-sec. after compression.

The density distribution of the plasma in the column is shown in Fig. 4. As will be seen from the graphs, the plasma stream is fairly sharply defined and its diameter, at density level 0.1 short of the maximum, is 5 cm. The maximum density is $n \simeq (0.5 \div 1)10^{13}$ cm.$^{-3}$

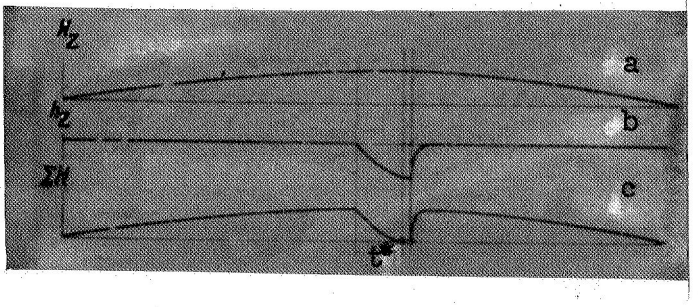


Fig. 2. Graphs showing changes in magnetic fields in terms of time.

a--quasi-constant magnetic field;
b--compensating magnetic field;
c--summed programmed field in injection area.

It should be noted that obtaining such a stable stream of plasma depends upon the selection of certain very definite conditions as regards the size of the magnetic fields (both quasi-stationary and compensating), the instant of injection, the degree of synchronization in the functioning of the injectors, and the symmetry with which the plasma fills the zero-field space. If these conditions are observed, the effectiveness of plasma confinement as it is compressed by a rapidly growing magnetic field ($H_{max} = 2 \div 2.5$ k-Oe., $dH/dt \simeq 8 \cdot 10^8$ oersteds/sec.) is quite good and approaches 100%. The trapped plasma spreads out in the homogenous magnetic field practically without losses.

Measurements were made of the induction current in order to determine the influence of electrodynamic forces upon the mechanism of the compression of the plasma. These measurements showed that plasma, as it is being compressed (with a full particle count $N \simeq (1 \div 5) \cdot 10^{16}$) has very little disturbing effect upon the outside magnetic field. /11

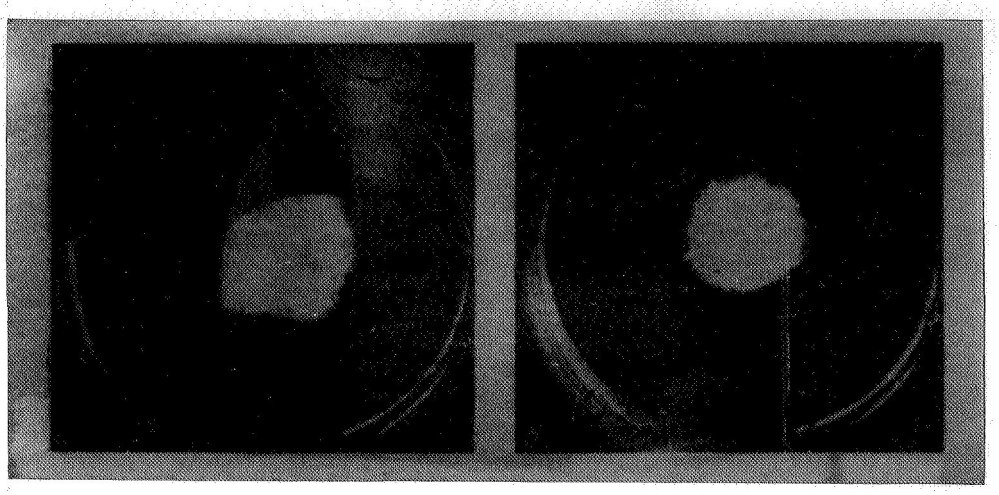
a  b

Fig. 3. Electronic image of the plasma thread on a luminescent screen: a) 6 μ-sec., and b) 30 μ-sec. after compression.

Thus the investigations carried out showed the possibility of injecting plasma by the method of irreversible change in the configuration of the magnetic field.

In order to investigate the effectiveness of the described method of injection into a closed toroidal trap with a double-helix field, preliminary tests were made with a semi-tore. The installation took the form of a vacuum chamber made of stainless steel (the large diameter being 1200 mm. and the small one--100mm.), around which were placed the windings of the lateral and the spiral field. The maximum size of the lateral, quasi-stationary magnetic field was 3,000 oersteds, while the ratio of the basic harmonic of the spiral field to the lateral field (ϵ) varied from zero to 0.7 [16]. A programmed field was created in the area of injection.

The results of the measurements showed that this method of injection is efficient enough under these conditions. The effectiveness of plasma containment is considerable and is affected but very little by the value of ϵ (when $\epsilon < 0.4$). As the spiral field increases further, containment efficiency declines. However, there is then a growing dependency upon the size of the magnetic field (when $\epsilon = 0.7$, the number of confined particles is three times smaller than it is with $\epsilon = 0$, but there is as yet no saturation when H = 3 kilo-oersteds.) It was also shown that the captured plasma spreads out along the half-

tore, drifting along the radius. Plasma losses at a turn with an angle of about 70 to 80° represent 30 to 35% ($\varepsilon = 0$). Such losses are perfectly natural and are due to the toroidal drift.

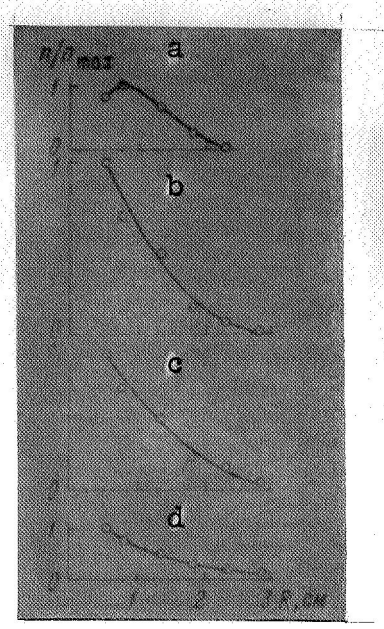


Fig. 4. Density distribution of the plasma along the radius of the vacuum chamber, at different instants following injection:

a—5.5 μ-sec. after injection; b—10.5 μ-sec.; c—15.5 μ-sec., and, d—28 μ-sec. The value of n_{max} is $8 \cdot 10^{11}$ and $9.5 \cdot 10^{11}$ cm^{-3} for b and c, respectively.

It could be expected that transition to a closed system in the presence of a spiral transformation of the magnetic field would sharply alter the character of the filling of the trap before the establishment of a balanced density distribution. This is indeed so, as will be seen from the results of experiments described in §3 below.

2. Plasma injection along a tube following the lines of force of the magnetic field brought outside the trap space (Refs. 12 and 17).

Investigation of the parameters of plasma sources shows that modern injectors do not generate a pure hydrogen or pure deuterium plasma; a certain amount of heavier ions as well as neutral atoms are always present. It seemed logical therefore to devise a method of injection which would not only satisfy the requirements dictated by the specifics of a closed trap, but would also make it possible to purify the plasma.

The idea of this method consists of the following. The central

tube which follows the lines of force of a double-helix closed stellarator field is brought out, with the aid of additional windings, beyond the confines of the trap and injection then takes place along the newly-formed magnetic conduit, with the use of an intermediate purification system [18]. After injection is completed, the magnetic lines of force must interlock within a time interval that is shorter than the one required to fill the gap. /13

One of the complex problems in this method of injection is the movement of a plasma of sufficient density ($n \simeq 10^{12} \div 10^{13}$ cm.$^{-3}$) in a curvilinear magnetic conduit.

As is known, a division of charges occurs in a plasma within a toroidal magnetic field. The electric field being generated causes the plasma to shift across the field, in the direction in which the latter is waning. One might fear that such transversal movement would develop so fast that a true trajectory of the plasma clot in a curvilinear field would be almost a straight line. However, experimental investigations [11], [12] and [19] showed that the character of the movement differs significantly from that predicted in [20] and that the plasma stream partly follows a segment of the toroidal field. Nevertheless these papers do not present an overall picture of the movement of a plasma stream. This prompted us to carry out an investigation of the movement of a plasma stream in a curvilinear magnetic conduit. The conditions of the experiment approximated, as much as possible, the conditions of injection into an actual magnetic trap.

The measurements were carried out in an installation represented schematically in Fig. 5. The parameters of the device were as follows: diameter of the basic vacuum chamber was 12 cm. and its length--180 cm. The chamber was situated within a solenoid creating a quasi-stationary homogenous magnetic field H_0 ($H_{0\ max} = 1.5$ kOe.). At a distance of 40 cm. from one of the ends of the chamber, it was joined by two connecting tubes having a length of 50 cm. and a diameter of 6 cm., carrying the winding of the auxiliary solenoids. The maximum value of the fields in these solenoids was $H_1 = 4.5$ kOe. At the end of the auxiliary solenoid a spark gun was installed.

Measurements made with the aid of an electron beam showed that by varying the interrelation of the fields H_0 and H_1 it is possible to bring out the energy tube from the basic solenoid into the auxiliary one at practically any point of the chamber.

With the aid of a luminescent probe, an examination was conducted into the configuration of the plasma flow at various points in time and at various distances from the curvilinear segment of the field. These tests showed that the plasma spreading out in the field of the basic solenoid consists of two parts (Fig. 6). One part--the nucleus--spreads out along the lines of force. As was shown by measurements of the electric field carried out with the aid of a twin probe, this nucleus is limited by a system of closed equipotentials which indicate the presence in the plasma of a radial electric field. The second part--the "tail"--represents plasma

drifting across the magnetic field along the full length of the flow. The drift is caused by an electric field generated as a result of the division of charges in the plasma, as it moves in the curvilinear magnetic field. An instant in the distribution of potential in the cross section of the plasma flow is shown in Fig. 7. The drift of the plasma along the full

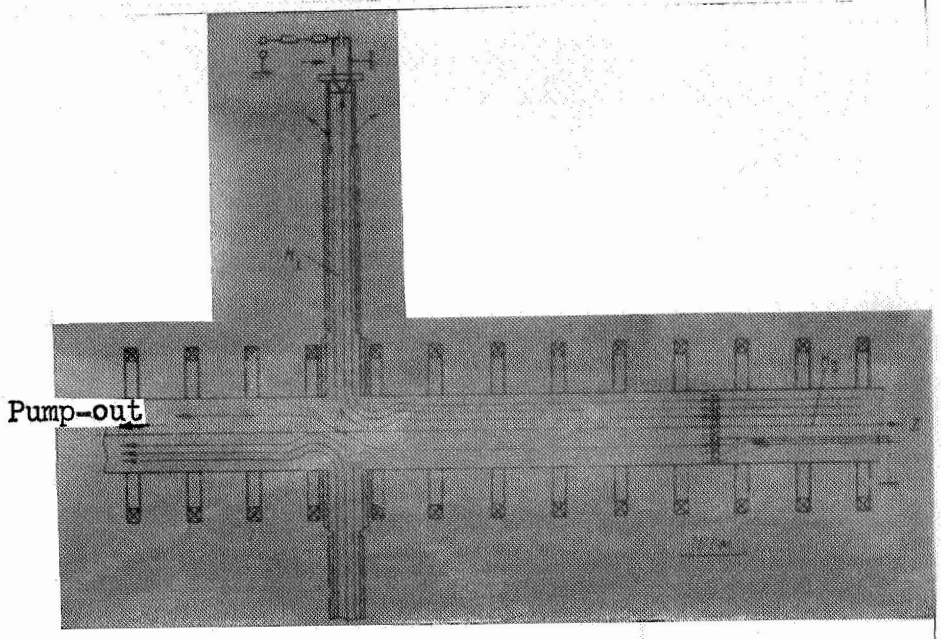


Fig. 5. Diagram of installation for studying the movement of plasma in a curvilinear field. /12

At point 0, z = 0.

Fig. 6. Configuration of the plasma after passing a curvilinear section.

The luminescent screen is placed at a distance of z = 80 cm. from the turn. Time lapse from the instant of injection is: a) 7.2 μ-sec.; b) 5.6 μ-sec., and c) 31.5 μ-sec.

length of the flow is caused by the fact that polarization, arising in the curvilinear segment of the field, is spreading out along the flow following the lines of force.

Measurements of the full flow of plasma at a given cross-section showed that it declines substantially as the distance from the curvilinear section grows (Fig. 8). With an increase in the magnetic field, the full flow through a given section grows linearly, without achieving saturation at H_0 = 1.5 kOe. /14

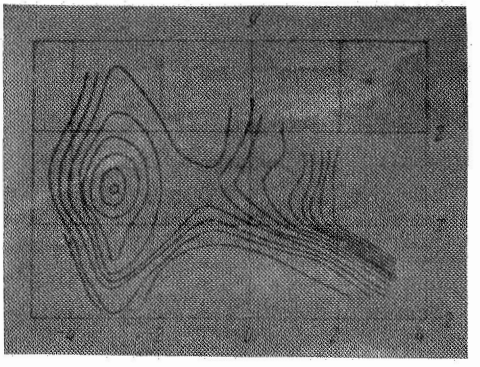


Fig. 7. Distribution of the potential in plasma. z = 40 cm., t = 10 μ-sec. The equipotentials are drawn through 2 v.

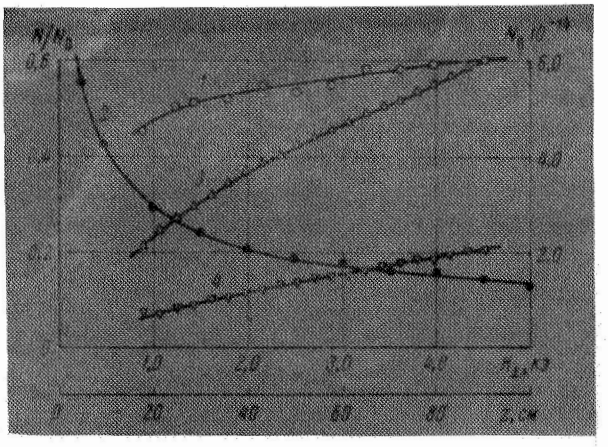


Fig. 8. Full plasma flow as a function of the value of magnetic field $H_\perp$ and the distance from turn z.

1—$N_0(N_\perp)$ at the outlet, without a turn; 2—N_z/N_0 when $N_\perp$ = 3 kOe.; 3 and 4—$N(H_\perp)N_0$ when z = 10 and 80 cm., respectively. $H_\perp/H_0$ = 3.

Efforts to reduce polarization of the plasma with the aid of a conductive surface did not achieve success. This, apparently, can be explained by the considerable resistance of the dual layer which is formed at the point of contact between the plasma and the conductor. The sum total of the experimental material referred to above (plasma images obtained with the aid of a luminescent probe showing the cross-section of the flow and the dependence of the full flow upon distance) positively indicates that considerable losses occur in a plasma flow moving in a homogenous field, after it goes through a turn. These losses are due to a drift of the plasma across the magnetic field under the influence of the azimuthal component of the electric field.

Further experimentation has shown that a reduction in plasma losses can be achieved by keeping the plasma away from the walls of the vacuum chamber.

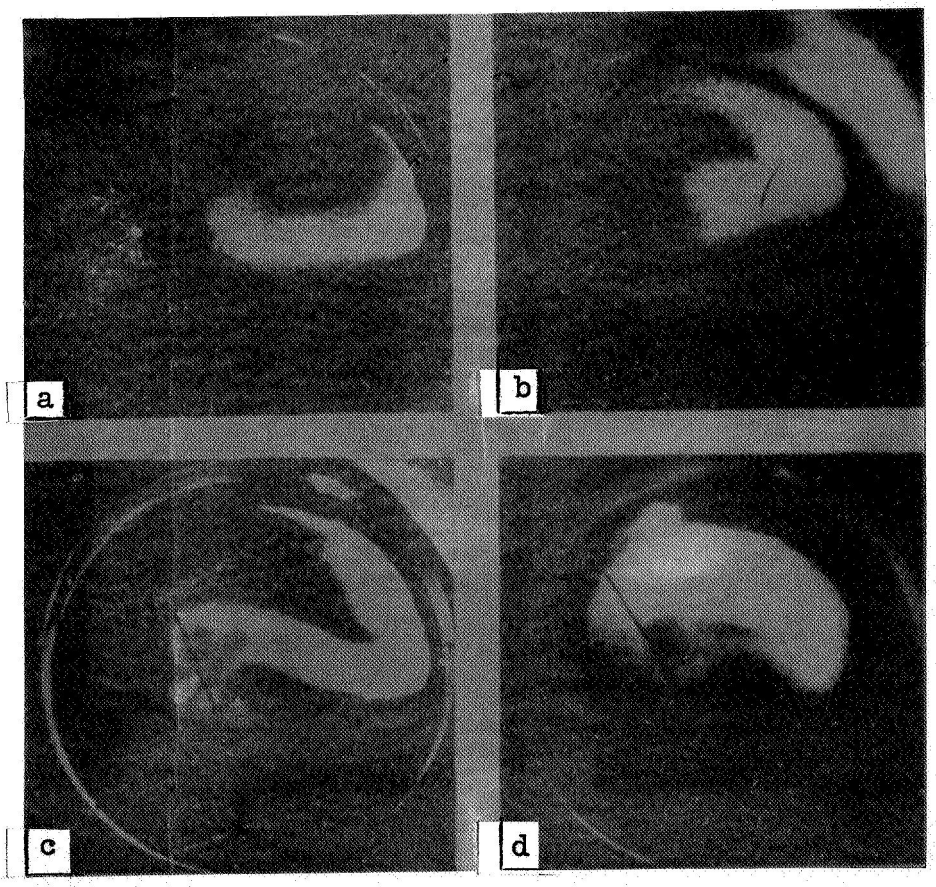


Fig. 9. Configuration of the plasma at a distance of 50 cm. (a and b) and 100 cm. (c and d) from the turn.

/15

Views a and b were obtained without a constraining tube within the chamber, while views c and d were taken with such a tube. Post-injection time was 10.3 μ-sec. for views a and b, and 15.9 μ-sec. for views c and d.

Separation of plasma from the chamber wall was obtained by means of reducing the effective cross-section of the chamber in the area of the curvilinear field. This was accomplished by inserting at this point a piece of stainless steel tubing (having a wall thickness of 0.2 mm., a diameter of 80 mm. and a length of 200 to 400 mm.) Measurements carried out with the aid of a luminescent probe (Fig. 9) showed that, in this case, the plasma stream is kept away from the walls throughout its duration and for the full length of the chamber. The diameter of the plasma stream, in such cases, equals that of the constraining tube.

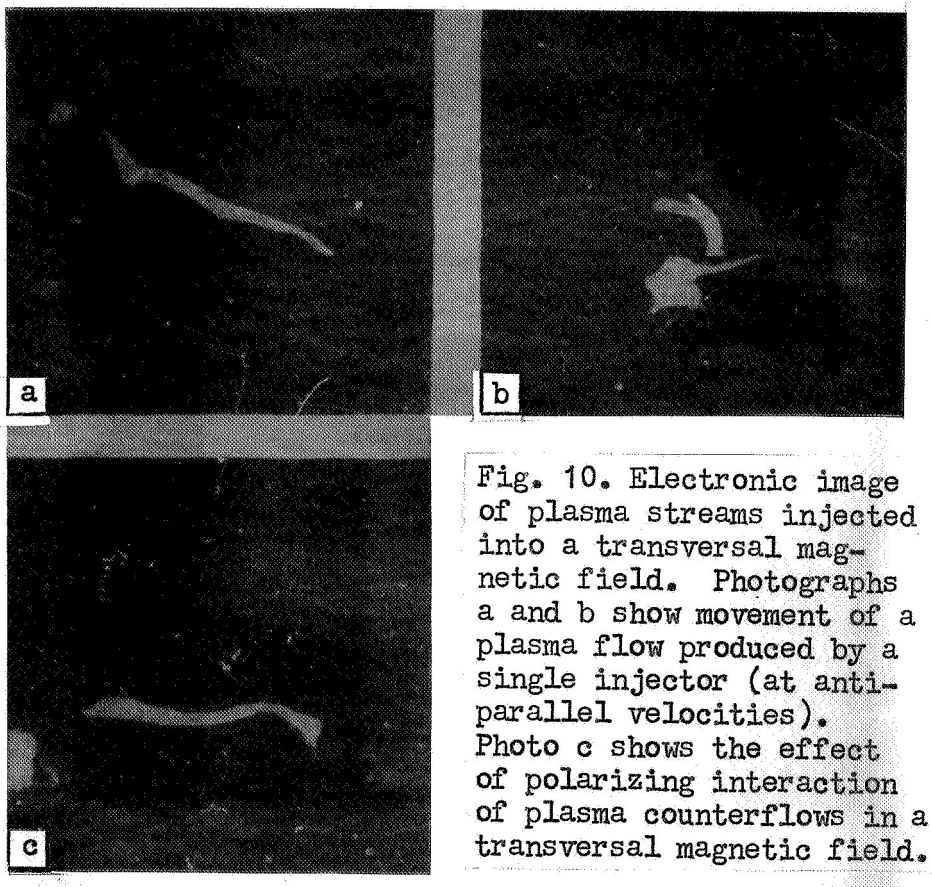


Fig. 10. Electronic image of plasma streams injected into a transversal magnetic field. Photographs a and b show movement of a plasma flow produced by a single injector (at anti-parallel velocities). Photo c shows the effect of polarizing interaction of plasma counterflows in a transversal magnetic field.

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From an analysis of photographs shown in Fig. 9 it is clear that the plasma, once it emerges from the constraining tube, shows no tendency to drift toward the walls of the chamber. Moreover, a clearly defined azimuthal drift can be observed which, at a distance of 100 cm. from the end of the constraining tube, alters the configuration of the plasma stream. Measurements of the full plasma stream as a function of distance show that there is a substantial decline in the amount of particles lost as the plasma spreads and that the efficiency of plasma confinement is increased. It can be assumed that so important a change in the behavior

of the plasma must be due to a destruction of the polarized azimuthal field and the development of a radial electrical field.

The results of the latest experiments justify the hope that this method of injection, combined with a purification of the plasma from impurities, may prove to be an effective way of filling a closed toroidal trap with pure plasma.

3. Collision of Plasma Streams in the Trap's Transversal Magnetic Field.

A study of the interaction of colliding plasma streams is of great interest because of the possibility of chaotization of directed velocities which, in modern plasma guns, attain a magnitude of from 10^7 to 10^8 cm/sec. Effective braking could thus generate a sufficiently high temperature in the plasma.

A number of authors have studied the movement of plasma in a transversal magnetic field [9] and [10]. One of the interesting results obtained in these papers has to do with the effect of polarizing interaction of several plasma flows, which could lead to a total stoppage of the colliding flows.

We have carried out experiments designed to study this interaction, and the results obtained have provided the basis for applying this method to the injection of plasma into a closed magnetic trap.

Fig. 10 shows photographs of electronic images of colliding plasma streams, obtained with the aid of a luminescent probe. Plasma injected by a single injector smoothly penetrates the magnetic barrier, but then the counterflows begin an intensive counteraction, which results in a sharp braking effect.

Study of such plasma injection was carried out in an installation with a double-helix stellarator field. [21]. The parameters of the device were as follows: The large radius of the toroidal vacuum chamber was 600 mm., the small radius--50 mm., the maximum value of the lateral field during the experiments $H_0 = 4.5$ kOe., the parameter $\epsilon = 0;\ 0.33 \div 0.7$; the magnetic field grows to a maximum in a sinusoid, during a time-interval of 2.7 μ-sec., and drops exponentially during a time constant of 7 μ-sec.; the working pressure in the chamber, $p = 10^{-6}$ mm. hg. In one of the sections of the vacuum chamber four spark guns were installed, which generated plasma during 0.4 μ-sec. The plasma was injected into fields of from 1500 to 2700 oersteds. Measurements were made with a dual Langmuir probe which could move both radially, in the chamber, over a distance of 50 mm., and in height (up to 10 mm. with respect to the median plane).

Measurements were carried out to determine the effectiveness of /17
simultaneous injection from several sources. When a single spark gun was used, the maximum density of the plasma did not exceed $5 \cdot 10^{10}$ cm.$^{-3}$. However, with the simultaneous use of two guns, plasma density increased

approximately four times. Such a quadrupling of the density is evidence of strong interaction between the plasma flows since if there had been no such interaction the plasma density would have merely doubled.

Fig. 12 shows the distribution of plasma density in a cross section of the chamber in its median plane ($\epsilon = 0.39$). An analysis of this distribution shows that the plasma has been drawn away from the wall and that its density is distributed more or less in a gaussoid, while the time-related decline in density occurs with a constant on the order of 500 μ-sec.

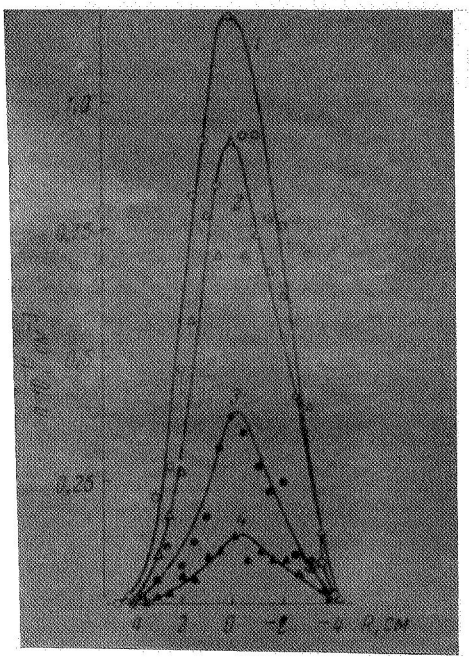

Fig. 11. Density distribution of the plasma in the cross-section of a vacuum chamber, at different points in time, t, following the injection of the plasma:
1--80 μ-sec.; 2--120 μ-sec.; 3--400 μ-sec.; 4--700 μ-sec.; $\epsilon = 0.39$; $T_e \approx 20$ ev.

From the fact of such time-related changes in these curves, it is possible to conclude that the time interval required to bring about a stationary density distribution within the trap is on the order of R/v_{tf}, where R is the radius of the chamber and v_{tf} is the mean velocity

of the distribution of plasma ions along the magnetic trap field (tf).

To illustrate the effectiveness of helicoidal windings, the density distribution of the plasma was measured over a cross-section of the chamber in the absence of any helical field. (As is known, plasma in such a field is unstable and drifts toward the wall, in a direction away from the center of the tore). The conditions of the experiment were the same as in the previous case: the injection was carried out in a field of 2,000 oersteds and two spark guns were operating simultaneously. Fig. 12 shows the density distribution at several points in time, following the injection of the plasma into the toroidal field.

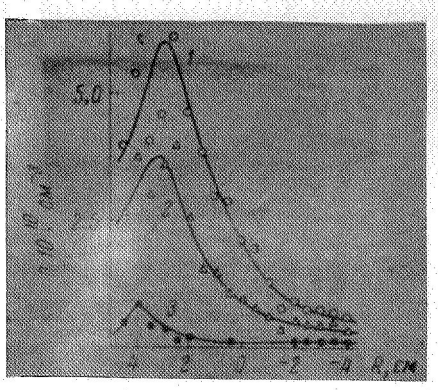

Fig. 12. Plasma density distribution in a cross-section of the vacuum chamber, at different instants: 1—80 μ-sec. after injection, 2—120 μ-sec., and 3—400 μ-sec.; $\epsilon = 0$, $T_e = 20$ ev.

As will be seen from Fig. 12, the peak density of the plasma has shifted from the center of the chamber in the direction of the outside wall of the tore, while in the case of injection into a stellarator field (Fig. 11), the density distribution is symmetrical with respect to the axis of the chamber. It is interesting to note that when the plasma is injected into a homogenous field, 400 μ-sec. later the distribution curve —for a large part of the chamber—becomes flat and a small peak is retained only near the outer wall. Thus the life span of the plasma is affected greatly by whether or not a helical field is present.

Fig. 13 shows two oscillograms in a case when a dual probe was installed in the center of the chamber. The first oscillogram was obtained as plasma was being injected into a stellarator field where $\epsilon = 0.39$, while the second one involved a toroidal field and $\epsilon = 0$. A comparison of these oscillograms as well as of the density distributions in Figs. 11 and 12 shows that the life span of the plasma is considerably greater in /18

a stellarator field than it is in a toroidal one. In the first case, the time constant attains 500 μ-sec., and in the second--less than 100 μ-sec. (It should be noted that life-span values obtained by probe measurements apparently were slightly reduced because of the loss of plasma particles to the probe).

The experimental data cited above permit the following conclusions:

In order to fill a closed magnetic trap, it is possible to use a method of injection based upon the polarizing interaction of colliding plasma streams;

It has been definitely established that a helical field has considerable effect upon the length of plasma confinement, the maximum density value of the trapped plasma, and its distribution along a section of the chamber.

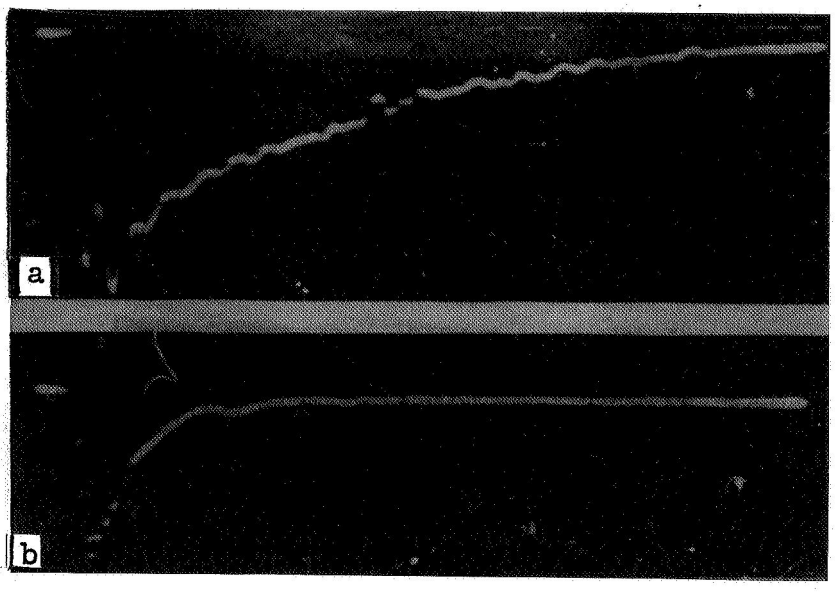

Fig. 13. Oscillograms produced with the use of a dual probe, situated in the center of the vacuum chamber.

a--helical field ($\epsilon = 0.39$); b--homogenous field ($\epsilon = 0$). Duration of span: 1 millisec.

CONCLUSION

The results of experiments involving the injection of plasma into a closed magnetic trap with a double helix stellarator field have shown the correctness of the general direction of these investigations. Plasma was injected into a closed trap with a helical magnetic field and this field

proved to have a great effect upon the duration of plasma confinement. Certain methods of injection were used with theoretical models and the results indicated these methods could also be used for the actual injection of plasma into a closed magnetic trap.

The method of a programmed magnetic field and the use of sources of pure plasma make it possible not only to achieve great effectiveness in plasma confinement, but also to increase the transversal energy of plasma ions as a result of shock compression by the rapidly growing magnetic field. Plasma injection with the use of a curvilinear magnetic conduit makes it possible to purify the plasma, ridding it of heavy impurities, and latest experiments with the use of a conductive liner in the chamber make it possible to increase still further the efficiency of the confinement.

It is thus clear, even now, that the difficulties encountered in injecting plasma into closed magnetic systems can be fully overcome. This fact will make it possible to consider, in an entirely different light, the possibilities of toroidal systems and will permit investigating the behavior of hot plasma in helical fields. The road in this direction calls for a prior development of injectors of pure plasma, an investigation of possible methods of plasma purification, and a study of the various mechanisms for heating the plasma. It is difficult to guess the ultimate results of such research. However, it undoubtedly opens a new and interesting experimental field in the physics of hot plasma.

In conclusion, the authors consider it their pleasant duty to express their appreciation to M. S. Rabinovich for his constant attention to the work in progress and useful discussions both as to the results of the experiments and the selection of their basic direction.

The authors also wish to thank the group of their co-workers which took part in the assembly and adjustment of the physical installations and in the carrying out of the experiments: E. P. Aleksandrov, M. S. Berezhetskiy, N. M. Zverev, Yu. G. Krutikov, N. V. Perov, as well as to the shop team headed by V. P. Solov'yev.

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Translated for the National Aeronautics and Space Administration by Scripta Technica, Inc., NASw-1694.